Quarkonia Production at RHIC

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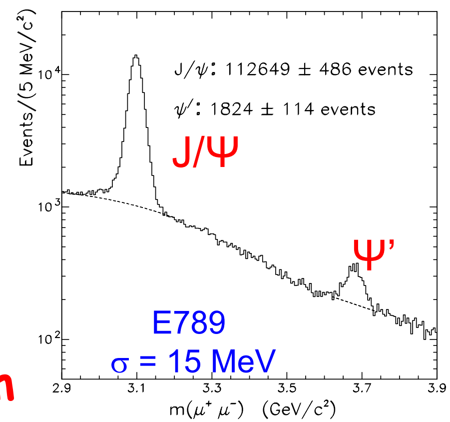
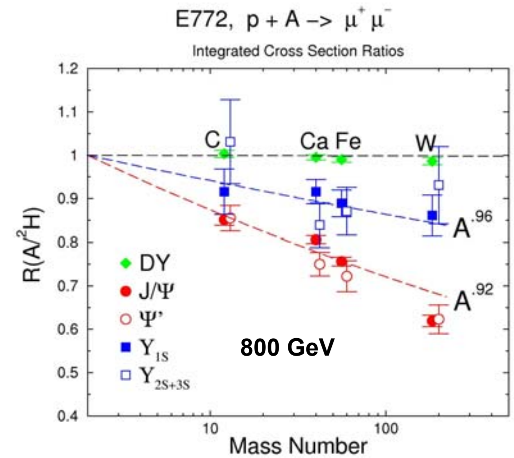
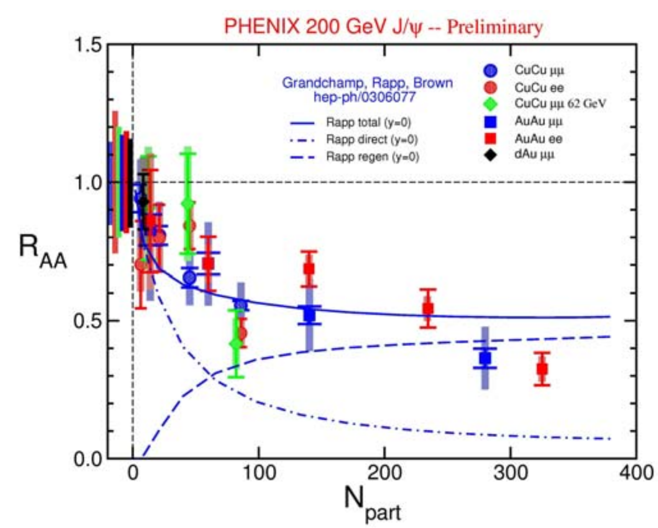
SQM - UCLA – 26-31 March 2006

- production
  - cross section & polarization
  - feed-down
- cold nuclear matter
  - shadowing or gluon saturation
  - absorption
  - gluon energy loss
  - contrasting open & closed charm
  - initial-state p_T broadening
- hot-dense matter in A-A collisions
  - PHENIX results
  - cold-nuclear matter effects in A+A
  - sequential suppression & regeneration
- future prospects
- summary







(see also talks by Johan Gonzalez, Andry Rakotozafindrabe, Andrew Glenn)

J/ψ production, parton level structure & dynamics

Production of heavy vector mesons, J/ψ, ψ′ and ϒ

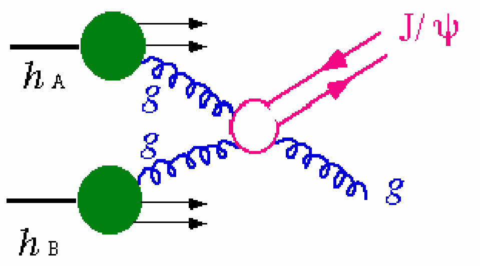
Gluon fusion dominates (NLO calculations add more complicated diagrams, but still mostly with gluons)

• production: color singlet or octet $c\bar{c}$: absolute cross section and polarization?

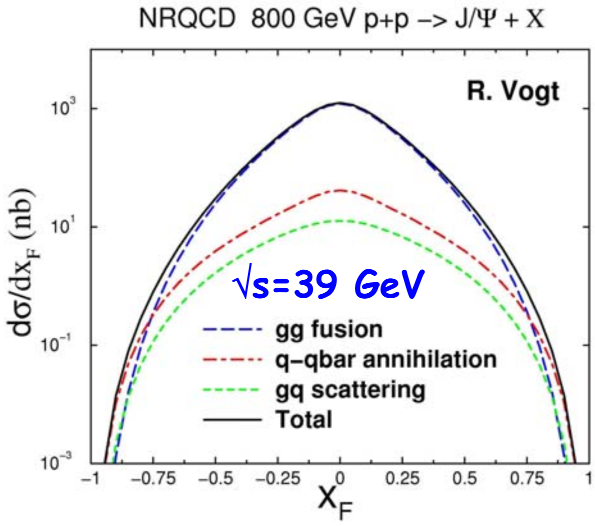
Hadronization time (important for pA nuclear effects)

Complications due to substantial feed-down from higher mass resonances, from ψ′, χ_c

$\chi_{,1,2} \to J/\psi$	~30%
$\psi' \to J/\psi$	5.5%

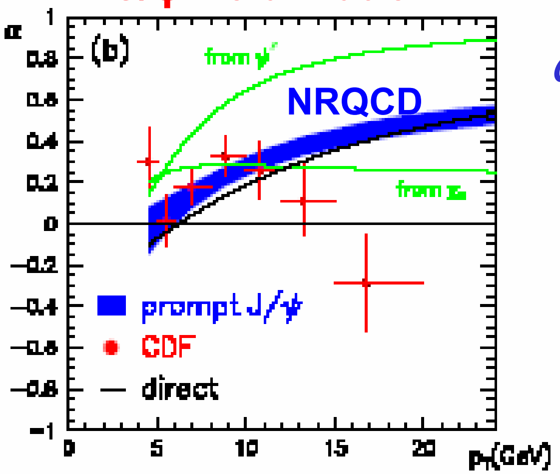


Phys.Rev. C61 (2000) 035203



J/ψ Production - Polarization

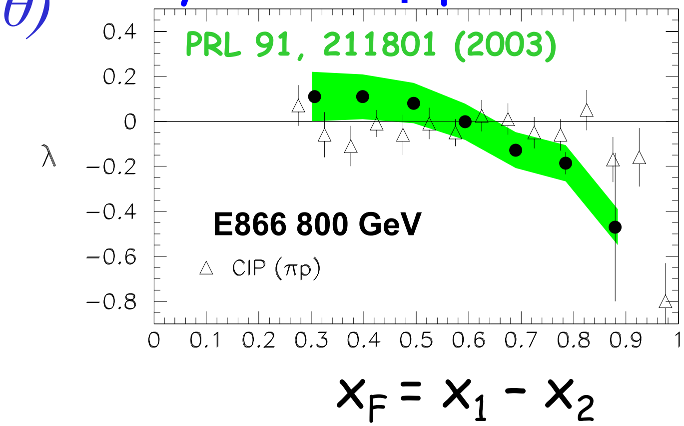
J/ψ Polarization



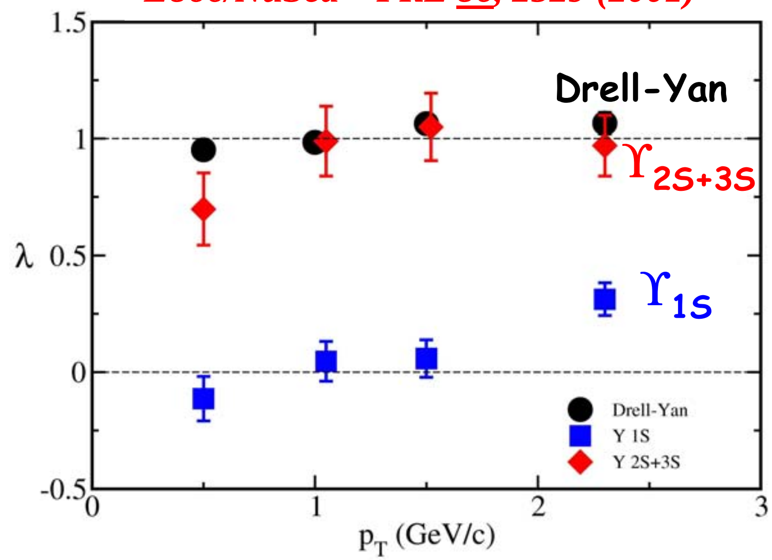
$$d\sigma/d\cos\theta = A(1+\lambda\cos^2\theta)$$

λ = +1 (transverse)
= -1 (longitudinal)

E866/NuSea
very small J/ψ polarization



E866/NuSea – PRL 86, 2529 (2001)



- Octet models get correct cross section size (unlike singlet), but…
- CDF and Fermilab E866 J/ψ data show little polarization & disagree with NRQCD predictions

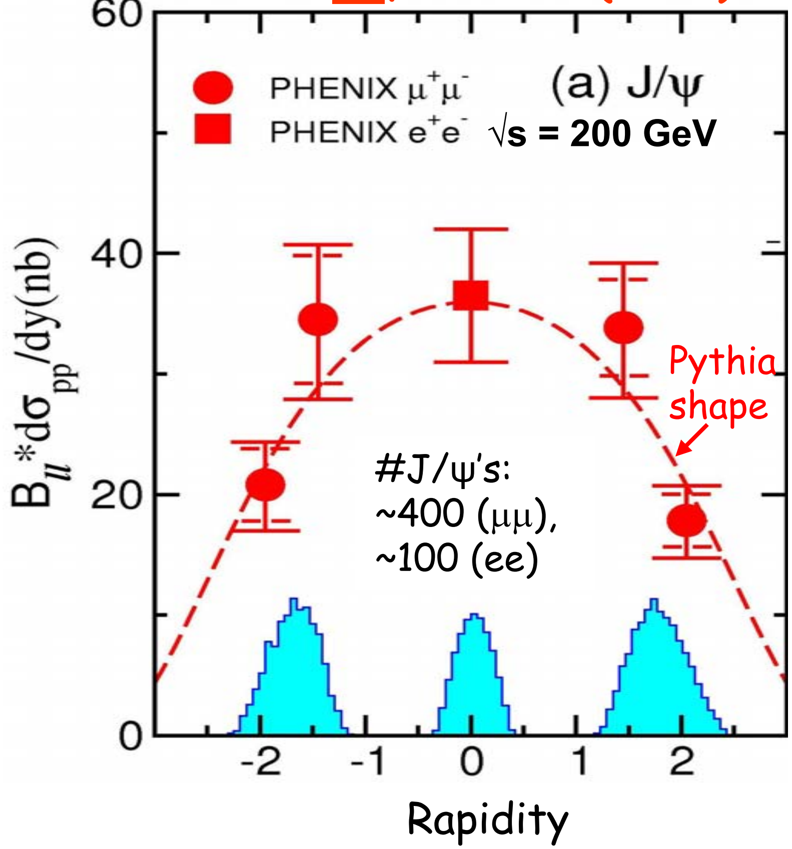
But Υ maximally polarized for (2S+3S), but NOT (1S)

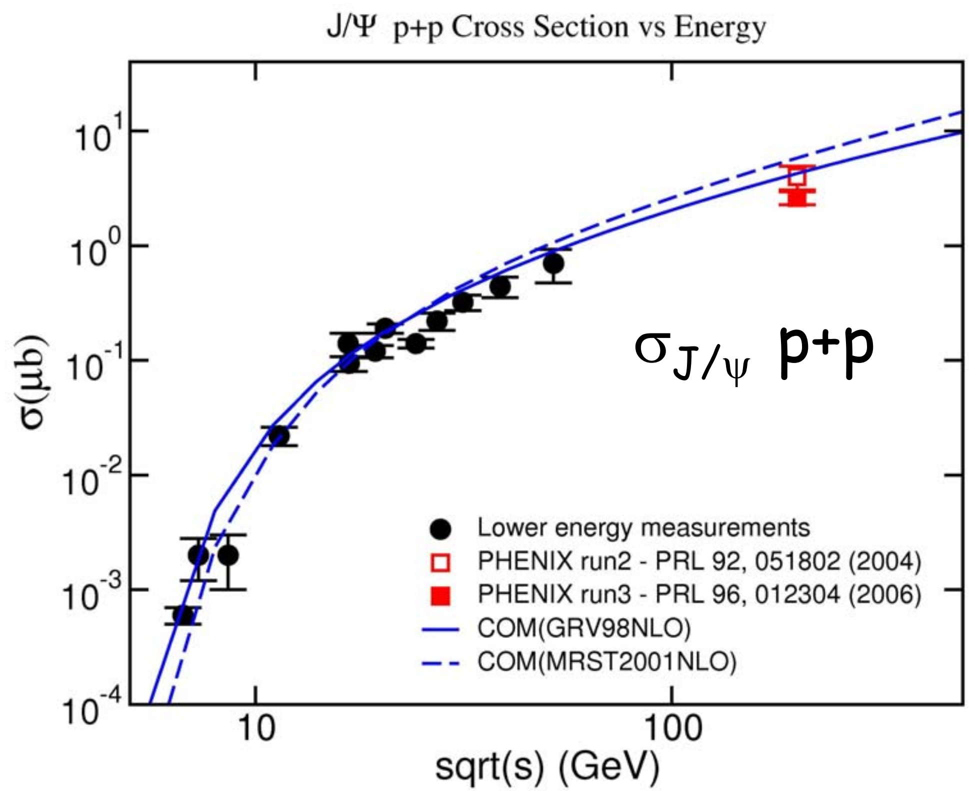
- Is feed-down washing out polarization? (~40% of 1S from feed-down)

(also need ψ' polarization measurement)

PHENIX - J/ψ cross section vs rapidity & √s

PRL 96, 012304 (2006)





More pp J/ψ's coming from PHENIX - ~5k/arm in 2005 run

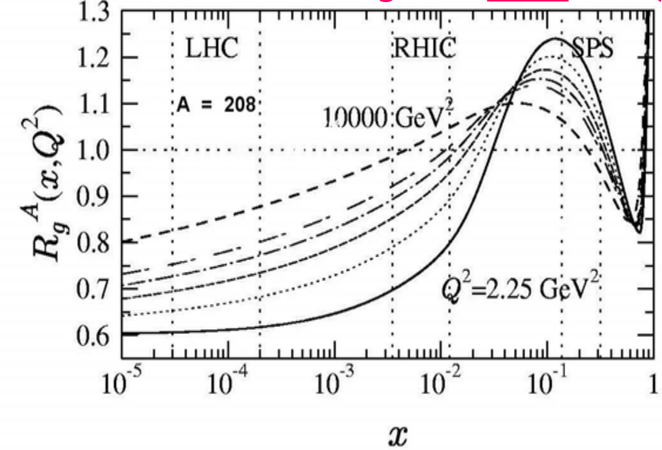
(ψ' may be coming soon, at least for e^+e^-, but higher luminosities will be needed to get significant # of counts)

Nuclear effects on Onia Production

Modification of parton momentum distributions of nucleons embedded in nuclei
- shadowing – depletion of low-momentum partons (gluons)
- coherence & dynamical shadowing
- gluon saturation at small x – e.g. Color Glass Condensate (CGC) model

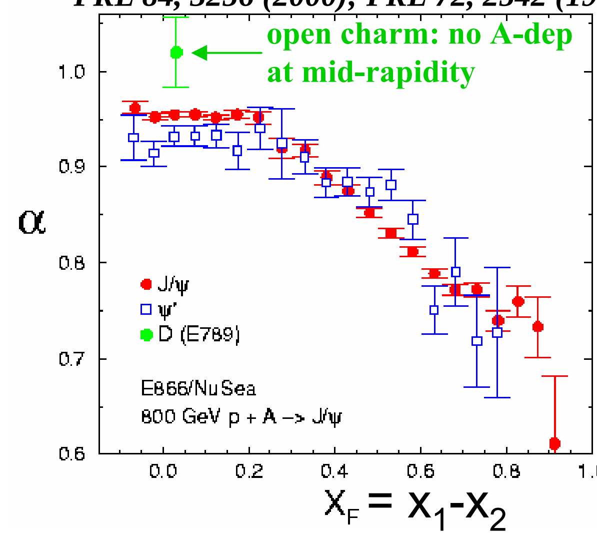
Nuclear effects on parton "dynamics"
- absorption (or disassociation) of J/ψ by nucleons or co-movers
- energy loss of partons as they propagate through nuclei
- multiple scattering effects (Cronin effect) causing p_T broadening

Eskola, Kolhinen, Vogt, NP A696, 729 (2001)

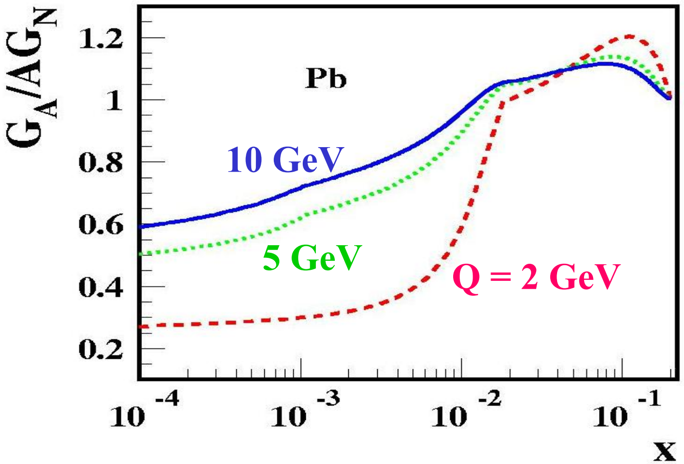


800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



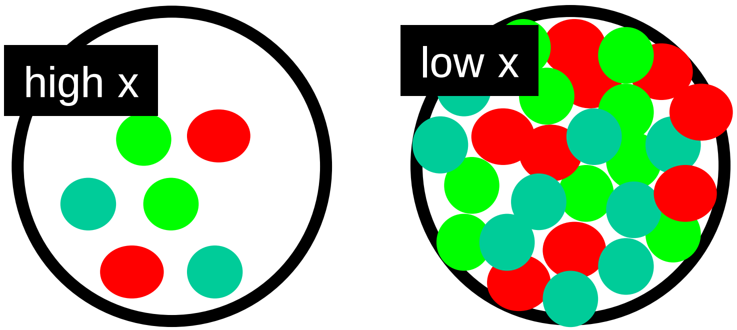
Gluon Shadowing and Saturation



Leading twist gluon shadowing, e.g.:

- Gerland, Frankfurt, Strikman, Stocker & Greiner - Eur. Phys. J A5, 293 (1999)
- phenomenological fit to DIS & Drell-Yan data, Eskola, Kolhinen, Vogt – Nucl. Phys. A696, 729 (2001).
- and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!



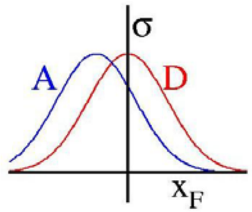
Saturation or Color Glass Condensate (CGC)

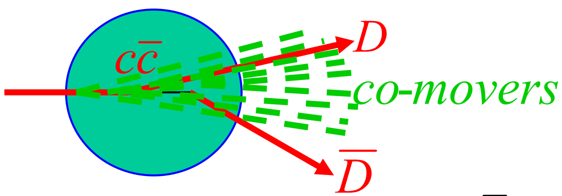
- At low-x there are so many gluons that 2→ 1 diagrams become important and deplete low-x region
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

The J/ψ - a Cold Nuclear Matter (CNM) Puzzle

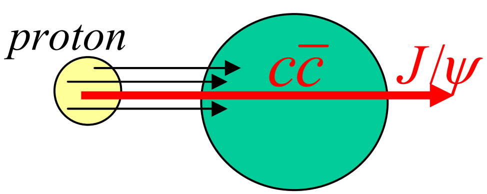
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:

Energy loss of incident gluon shifts effective x_F and produces nuclear suppression which increases with x_F





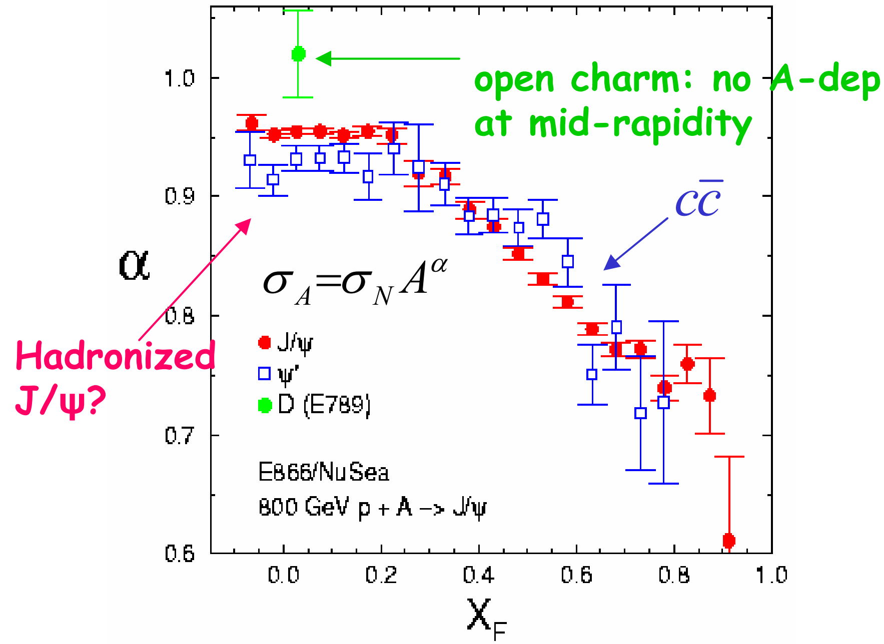
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)



Intrinsic charm components of incident proton produce J/ψ at large x_F. $A^{2/3}$ dependence from surface stripping of proton's light quarks (Brodsky)

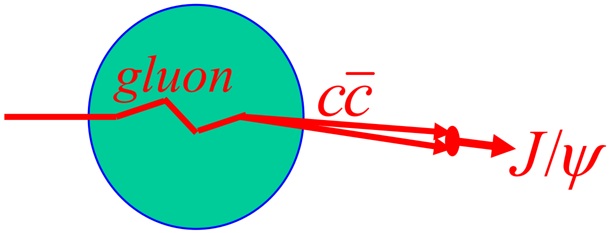
800 GeV p-A (FNAL)

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



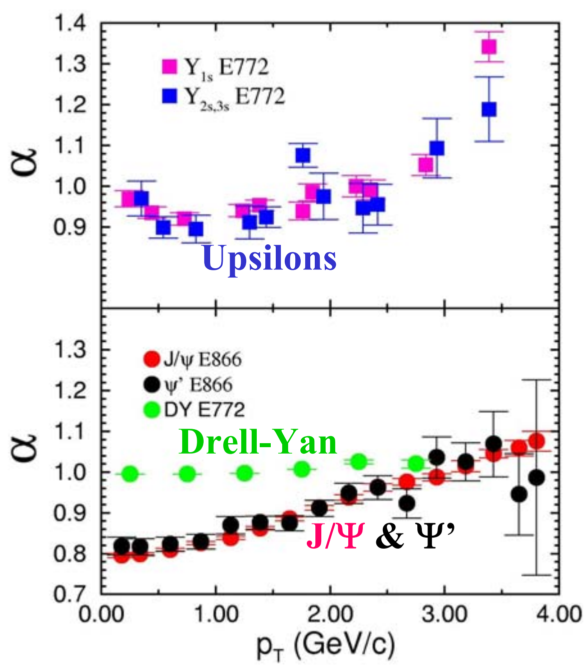
- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity (x_F ~ 0) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed at x_F ~ 0; what about at higher x_F?

Transverse Momentum Broadening for J/ψ's

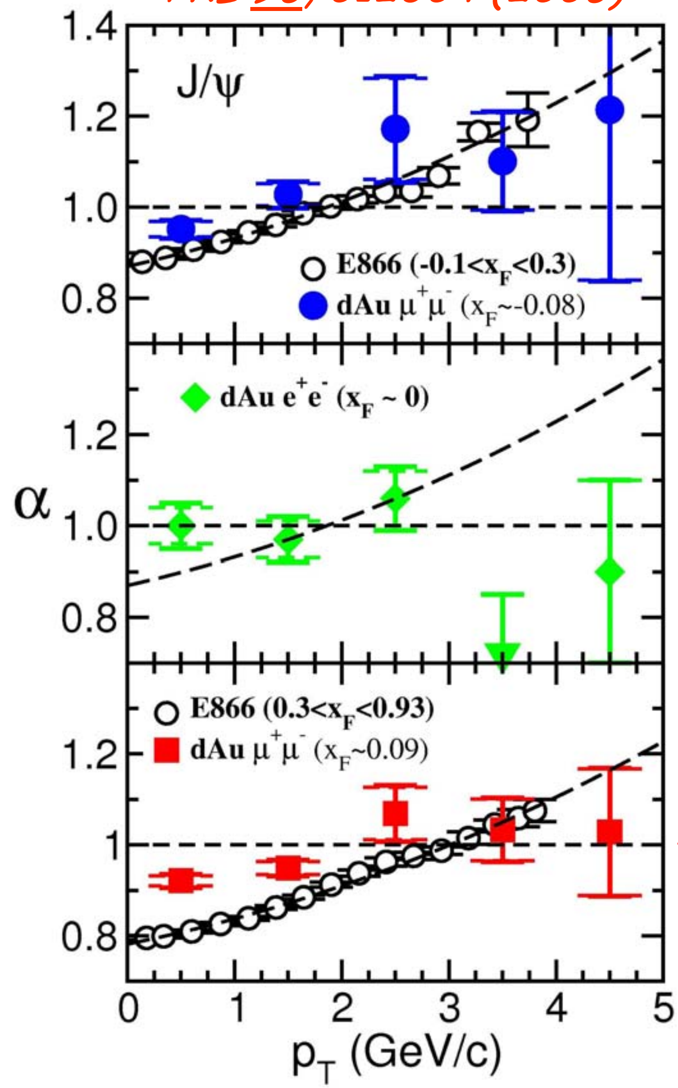


Initial-state gluon multiple scattering causes p_T **broadening** (or Cronin effect)

$$\sigma_A = \sigma_N A^{\alpha}$$



PRL 96, 012304 (2006)



High x_2 ~ 0.09

PHENIX 200 GeV results show p_T broadening comparable to that at lower energy ($\sqrt{s}$=39 GeV in E866/NuSea)

Low x_2 ~ 0.003

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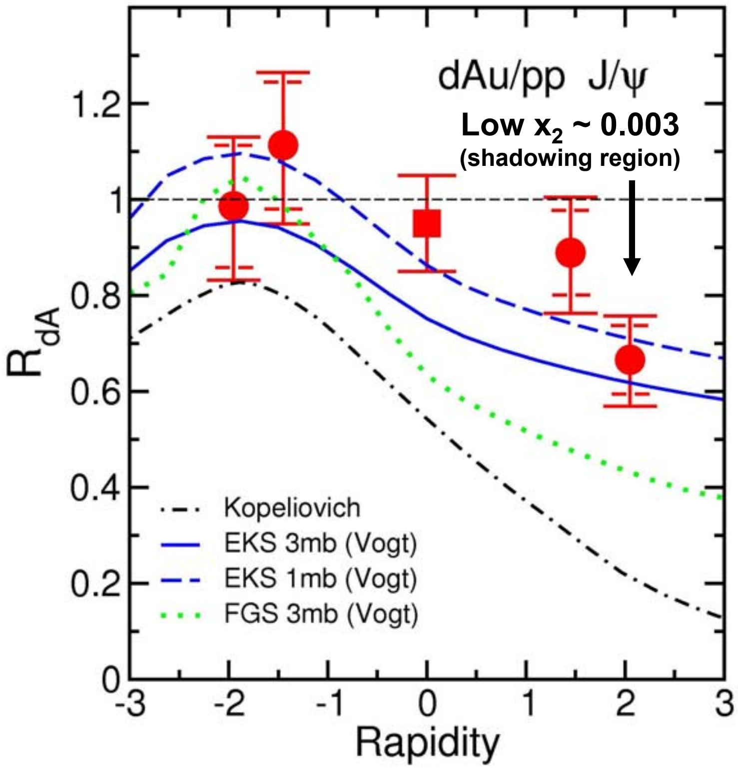
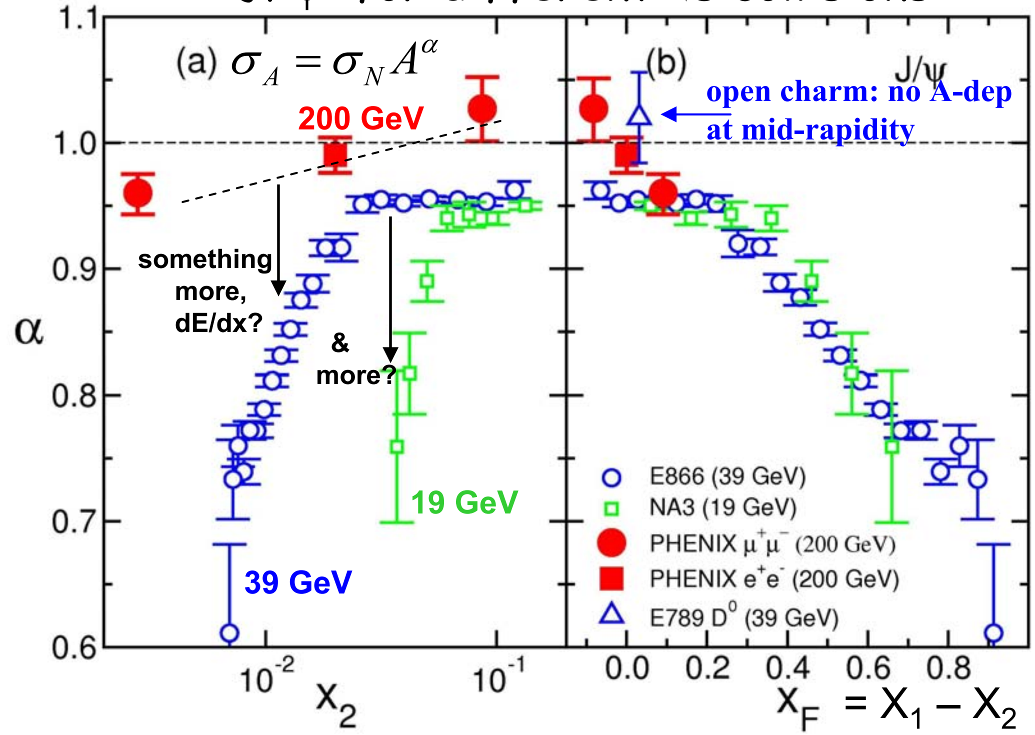
PHENIX J/ψ Nuclear Dependence for 200 GeV pp and dAu collisions – PRL 96, 012304 (2006)



Klein,Vogt, PRL 91:142301,2003

Kopeliovich, NP A696:669,2001

J/ψ for different √s collisions



Data favors weak shadowing & absorption

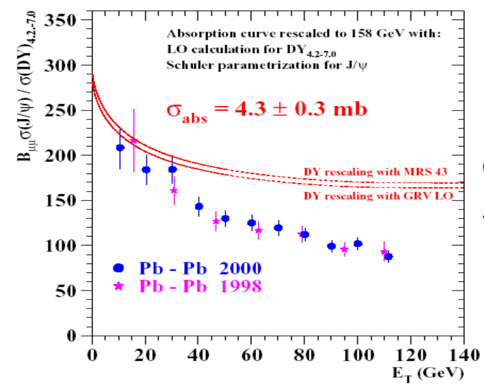
- With limited statistics difficult to disentangle nuclear effects
- Will need another dAu run! (more pp data also)

Not universal vs x_2 as expected for shadowing, but does scale with x_F, why?

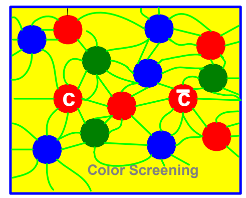
- initial-state gluon energy loss?
- Sudakov suppression (~energy conservation)?

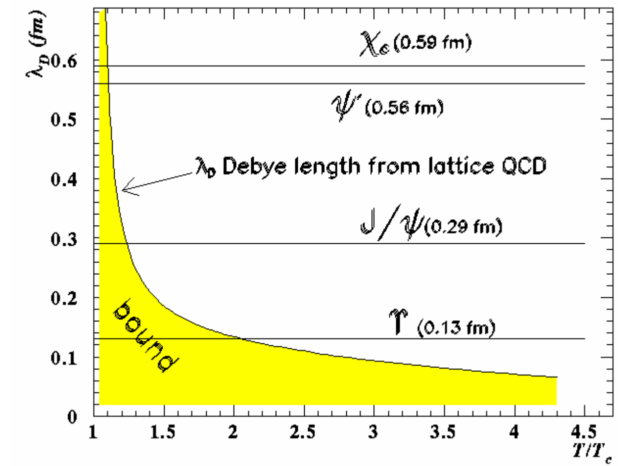
AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

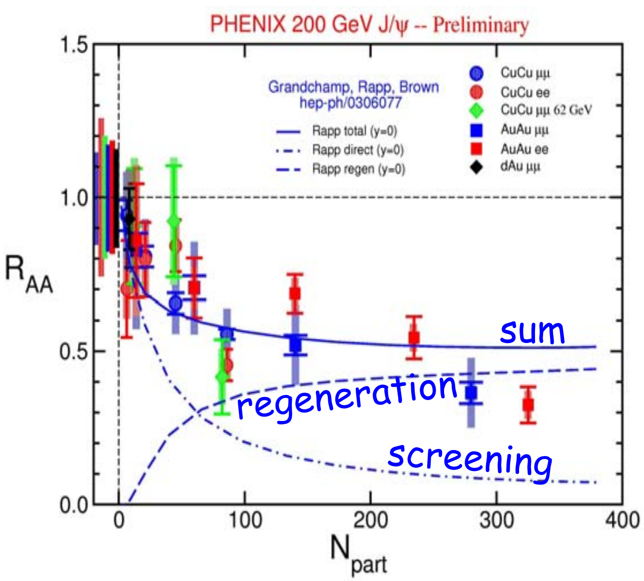
Debye screening predicted to destroy J/ψ's in a QGP with different states "melting" at different temperatures due to different binding energies.



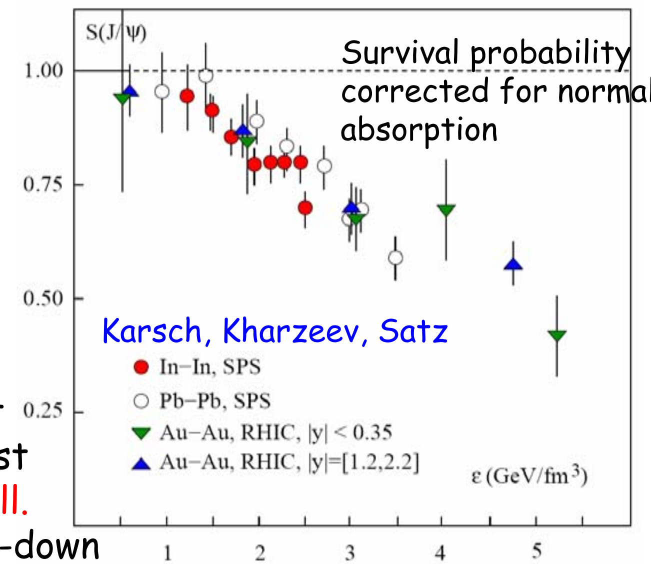
NA50 anomalous suppression







but recent regeneration models might give enhancement that compensates for screening?



on the other hand, recent lattice calculations suggest J/ψ not screened after all. Suppression only via feed-down from screened χ_C & ψ'

energy density

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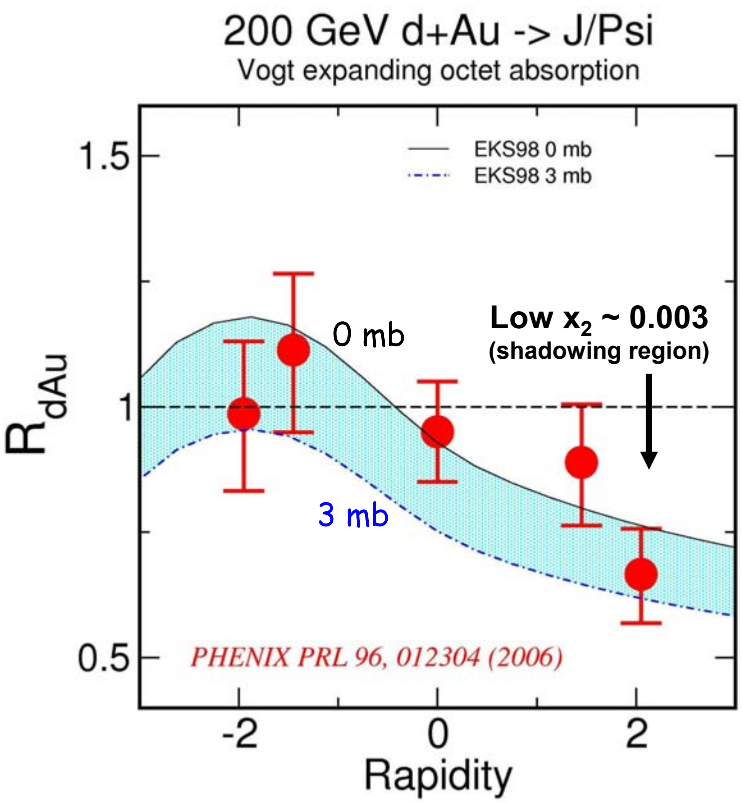
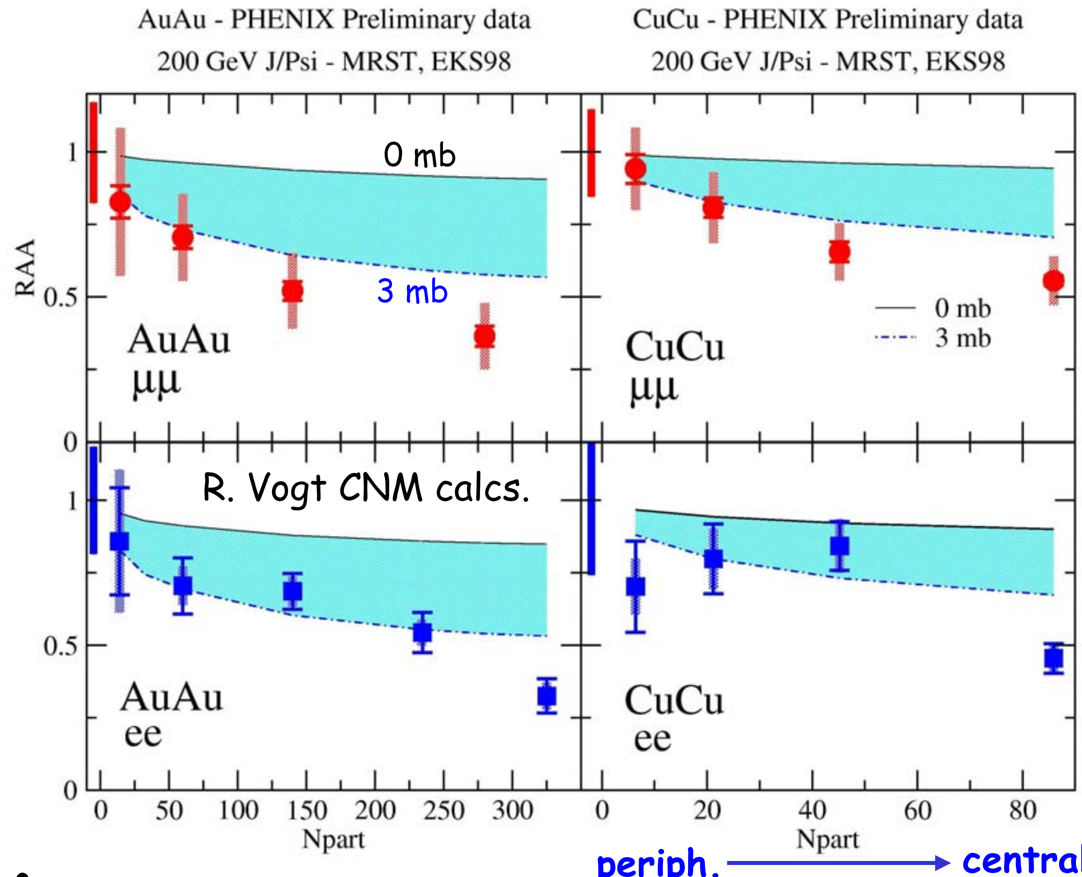
J/ψ suppression in AA collisions & CNM baseline

(CNM = Cold Nuclear Matter)

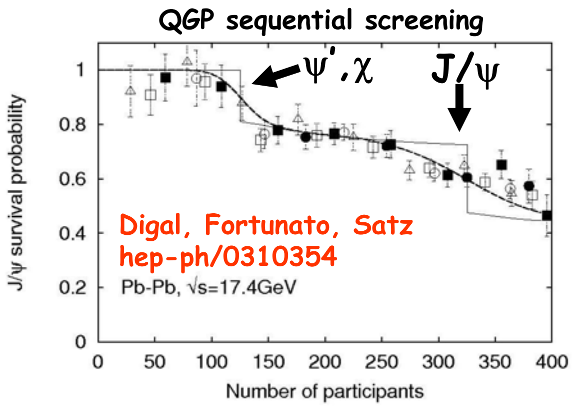


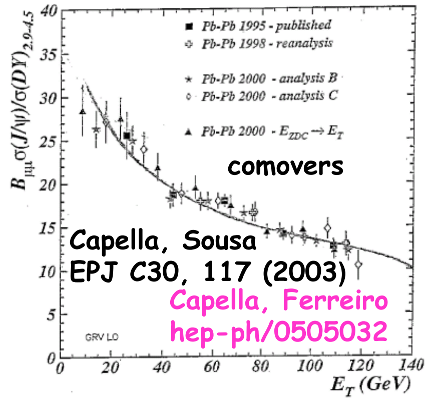


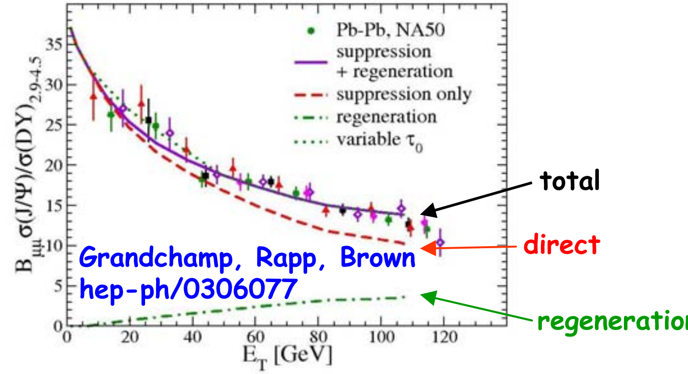
- CNM calculations with shadowing & absorption
- present dAu data probably only constrains absorption to: σ_{ABS} ~ 0-3 mb

- AA suppression is somewhat stronger than CNM calculations predict
- but really need more precise dAu constraint!

Models without regeneration

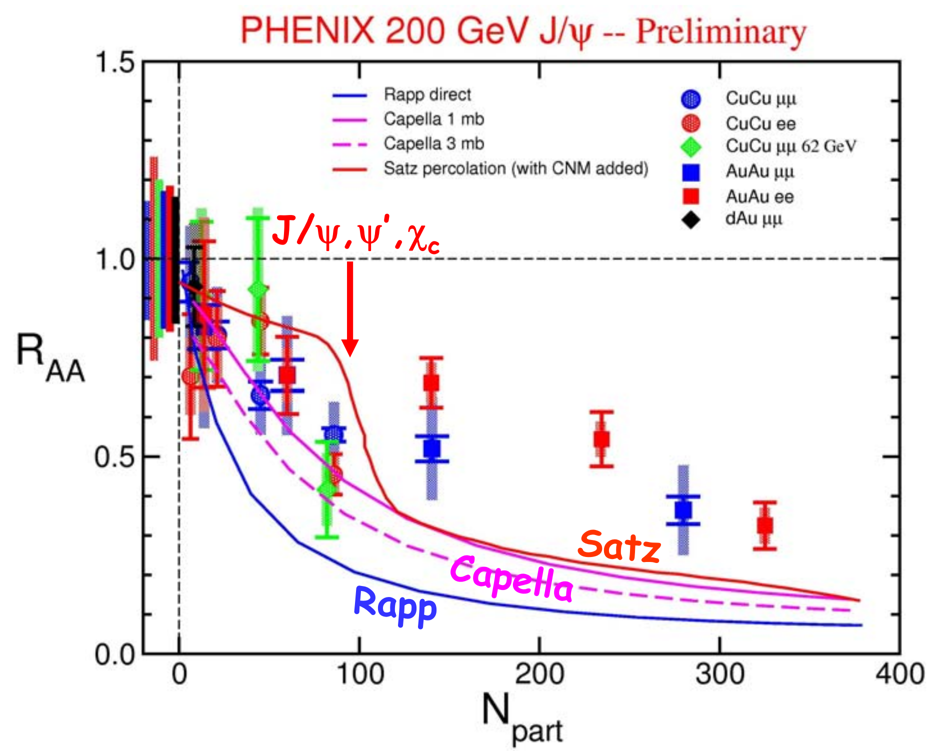






Models that reproduce NA50 results at lower energies predict too much suppression at RHIC!

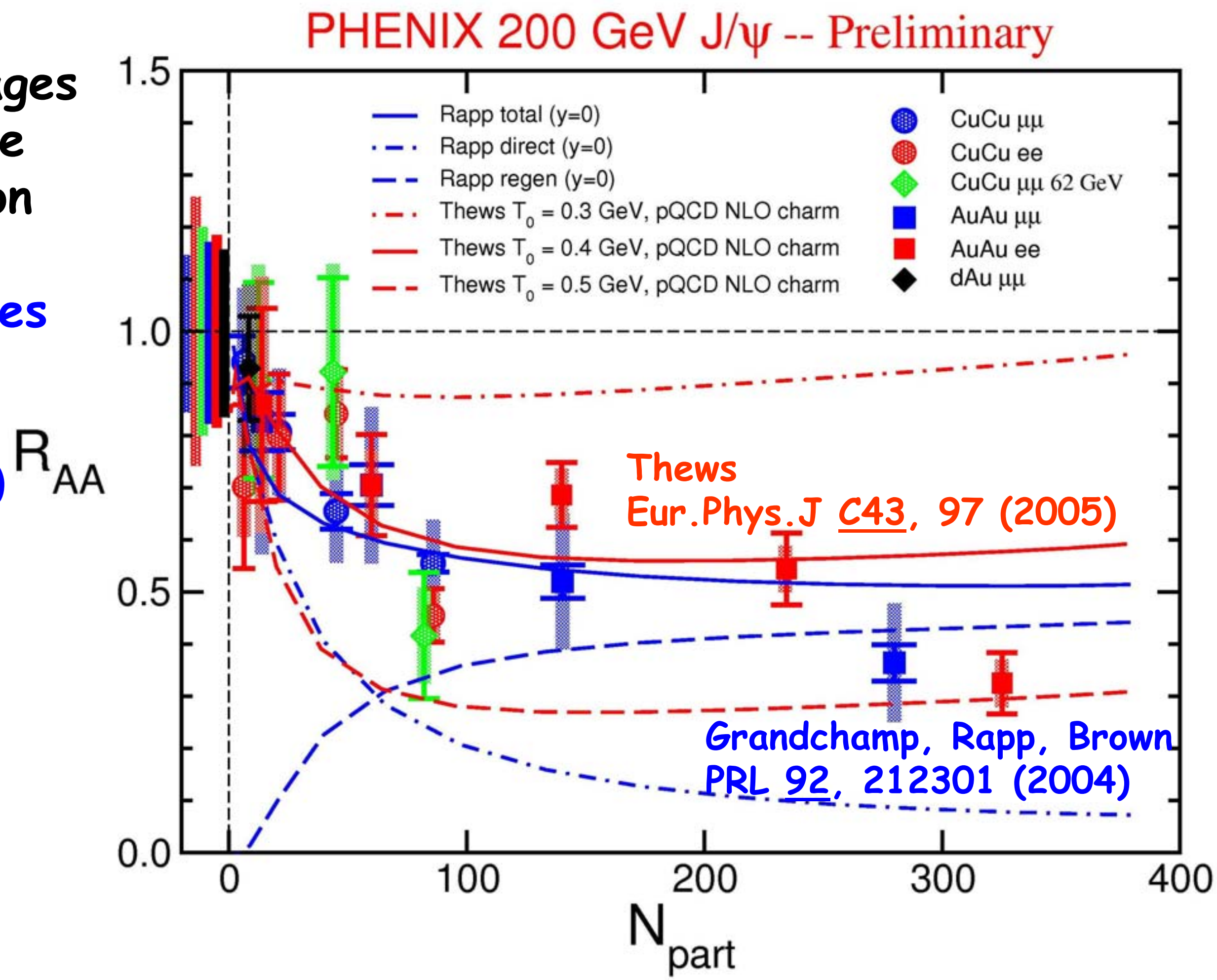
- Satz - color screening in QGP (percolation model) with CNM added (EKS shadowing + 1 mb)
- Capella – comovers with normal absorption and shadowing
- Rapp – direct production with CNM effects needs very little regeneration to match NA50 data

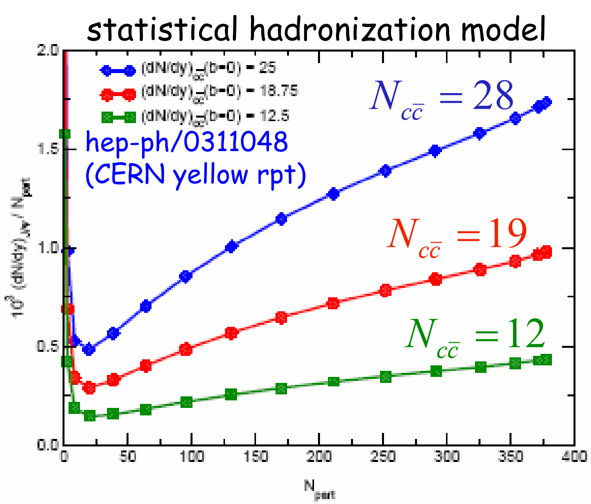


Models with screening & regeneration

Models with regeneration, i.e. single charm quarks combining in the later stages to form J/ψ's – match the observed RHIC suppression much better!

- **but the regeneration goes as $\sigma_{c\bar{c}}^{2}$ - which is still poorly known at RHIC (& that's another story..)**





Many More Models for RHIC J/ψ suppression in CuCu & AuAu Collisions

All have suppression + various regeneration mechanisms

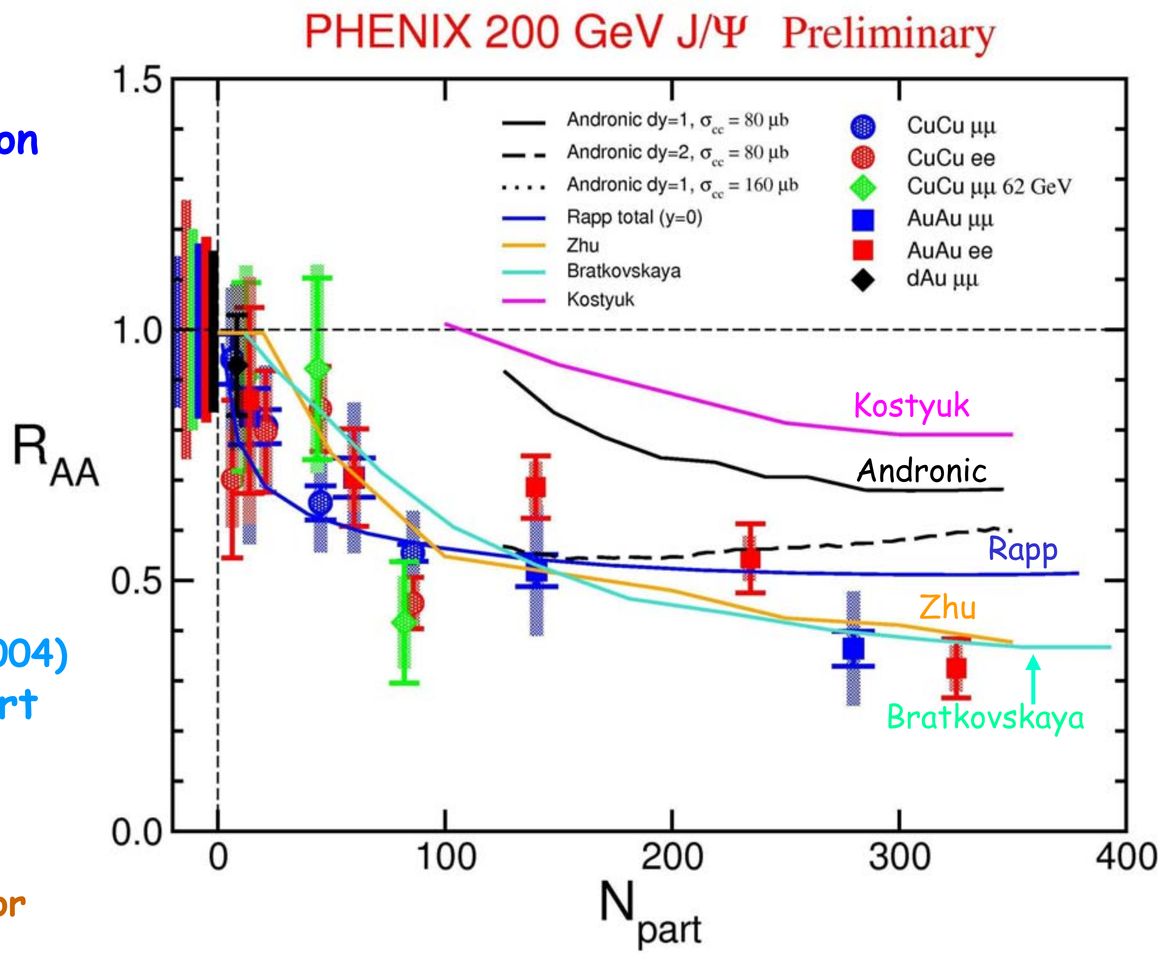
Rapp – PRL 92, 212301 (2004)
- screening & in-medium production

Thews – see previous slide

Andronic - PL B57, 136 (2003)
- statistical hadronization model
- screening of primary J/ψ's
- + statistical recombination of thermalized c-cbar's

Kostyuk – PRC 68, 041902 (2003)
- statistical coalescence
- + comovers or QGP screening

Bratkovskaya – PRC 69, 054903 (2004)
- hadron-string dynamics transport



Zhu - PL B607, 107 (2005)
- J/ψ transport in QGP
- co-movers, gluon breakup, hydro for QGP evolution
- no cold nuclear matter, no regeneration

Regeneration or Sequential Screening?

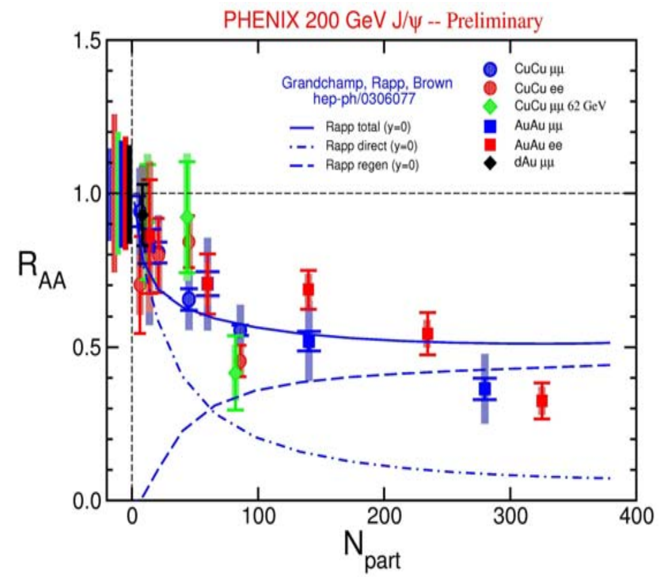
RHIC suppression looks same as that at NA50

- but ~10x collision energy & ~2-3x gluon energy density at RHIC
- regeneration compensates for stronger QGP suppression?
  - if so, regeneration would be huge at the LHC!

------------- OR -------------------

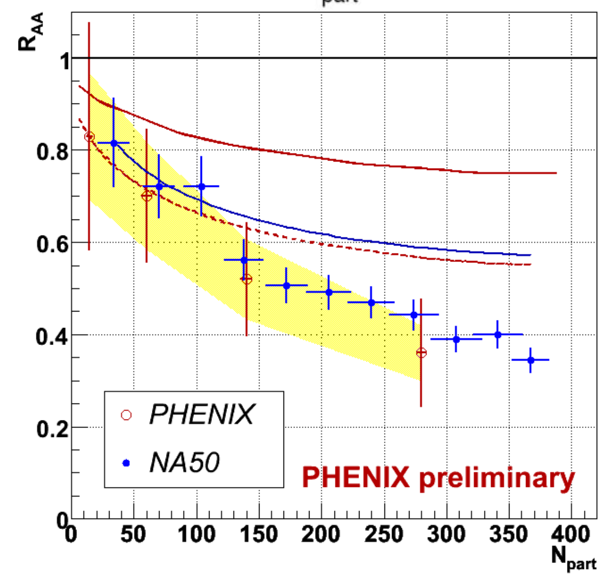
(Karsch, Kharzeev, Satz, hep-ph/0512239)

- Sequential screening of the higher-mass resonances that feed-down to the J/ψ; with the J/ψ itself still not dissolved?
- supported by recent Lattice calculations that give $T_{J/\psi} > 2\ T_C$



Quarkonium dissociation temperatures – Digal, Karsch, Satz

state	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.0	1.76	1.60	1.19	1.17

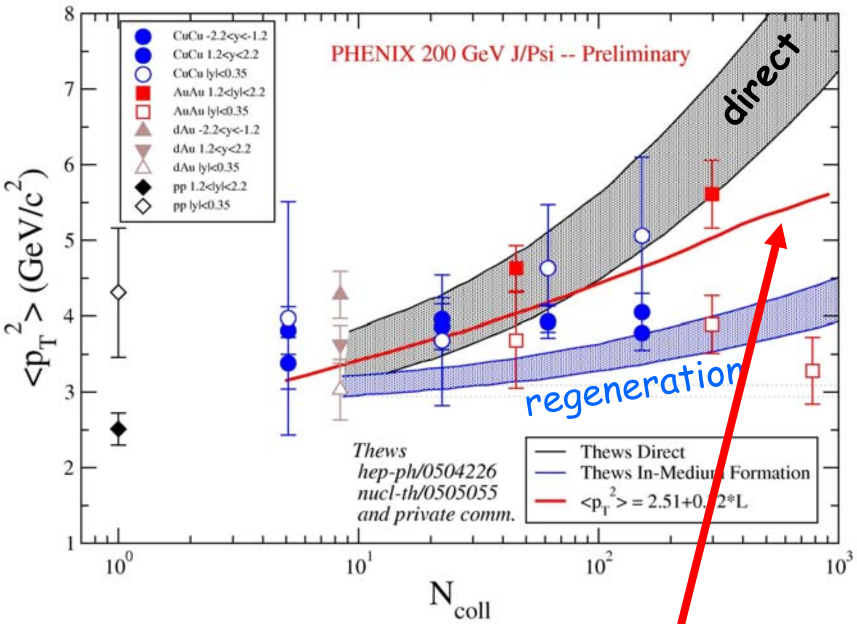


Regeneration should cause narrowing of p_T and y – does it?

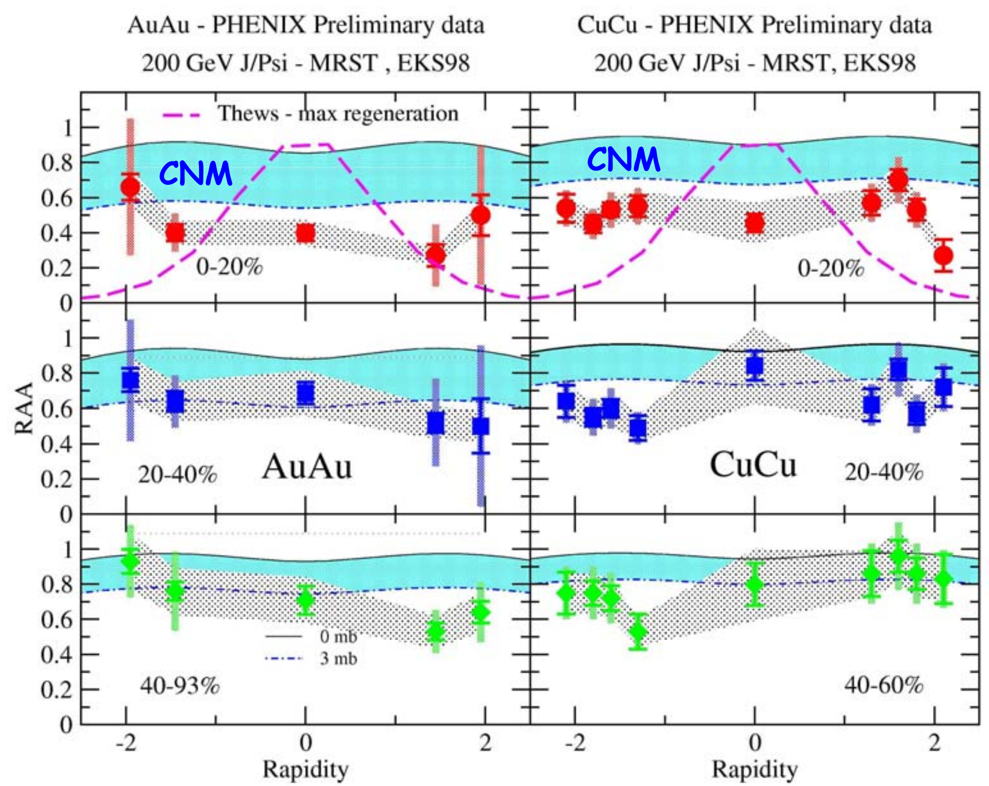
p_T broadening lies in between Thews direct & in-medium formation suggesting some regeneration (but our fit to pp+dAu data vs L also reasonable)

But rapidity dependence of central AA collisions (top panels) shows no narrowing – i.e. peaked ratios as in the Thews (maximal) regeneration, shown below

But careful – is σ_{ccbar} flatter with y than we originally thought?



$<p_T^2> = 2.51+0.32*L$
from fit to dAu data vs L



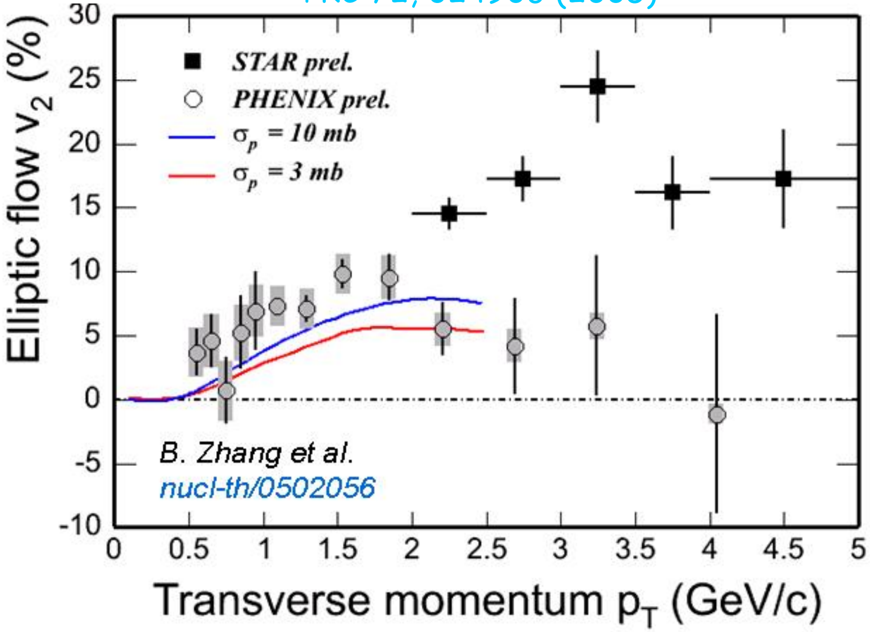
Flow of J/ψ's?

Need to look for J/ψ flow – if regeneration dominates, the J/ψ's should inherit flow from charm quarks

• open charm has recently been seen to flow (at least at some p_T values)

• but what about geometrical absorption effects, which could also give asymmetry wrt reaction plane?

PRC 72, 024906 (2005)



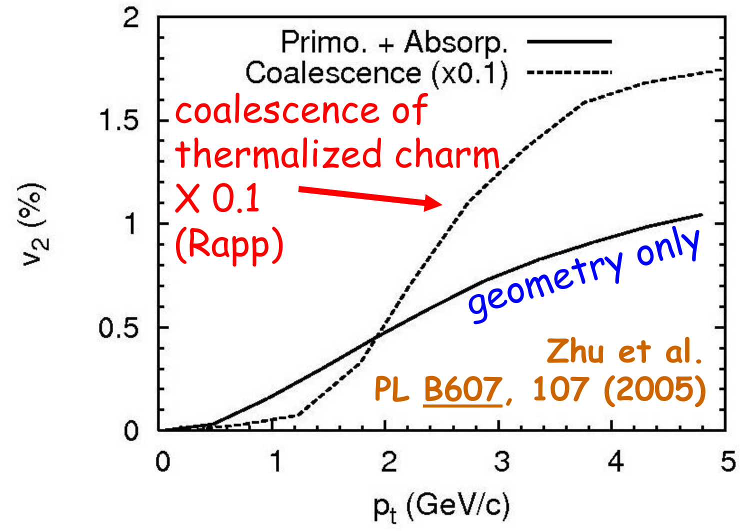
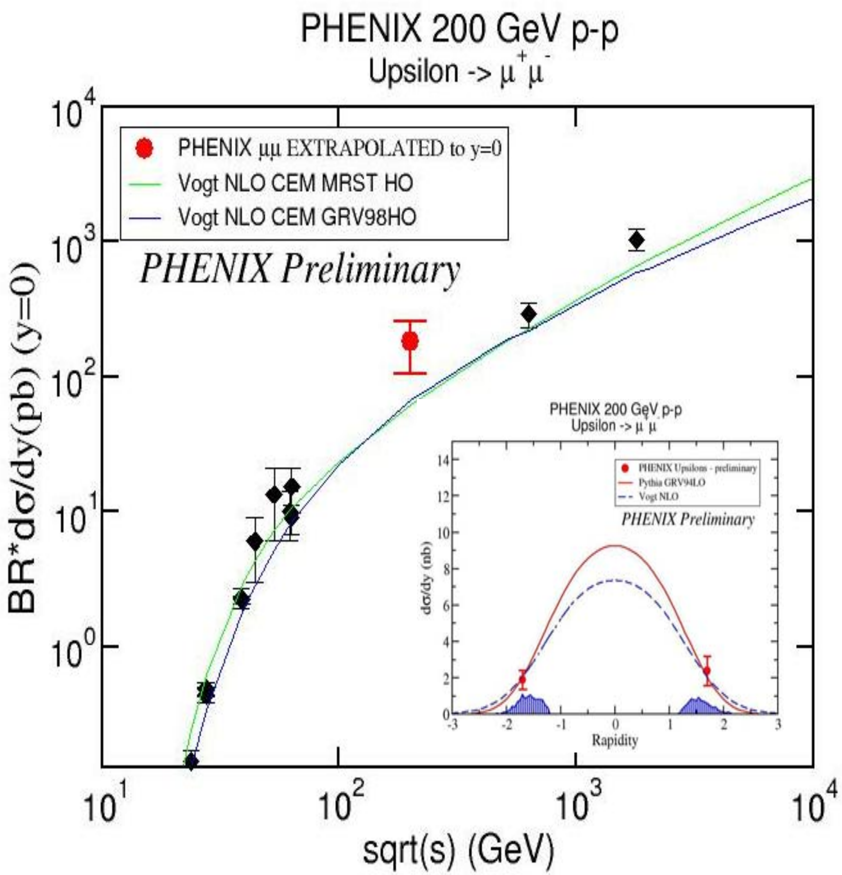


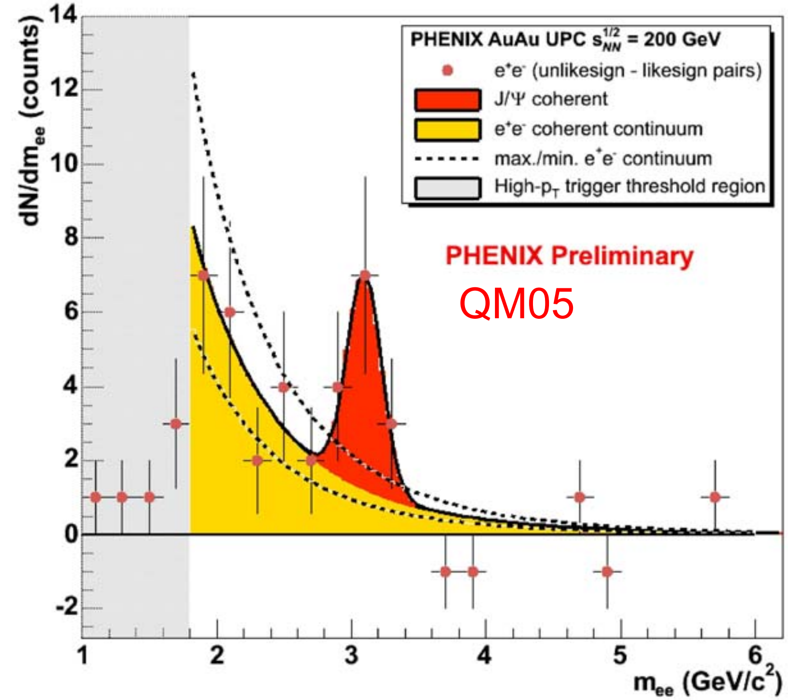
FIG. 4: The elliptical flow of J/ψ as a function of p_t at RHIC energy. The solid line is the maximal v_2 with impact parameter b=7.8 fm calculated in the frame of J/ψ transport, and the dashed line is the minimum-bias v_2 (scaled by a factor of 0.1) of the coalescence model with the assumption of complete charm quark thermalization.

Much More to Come!



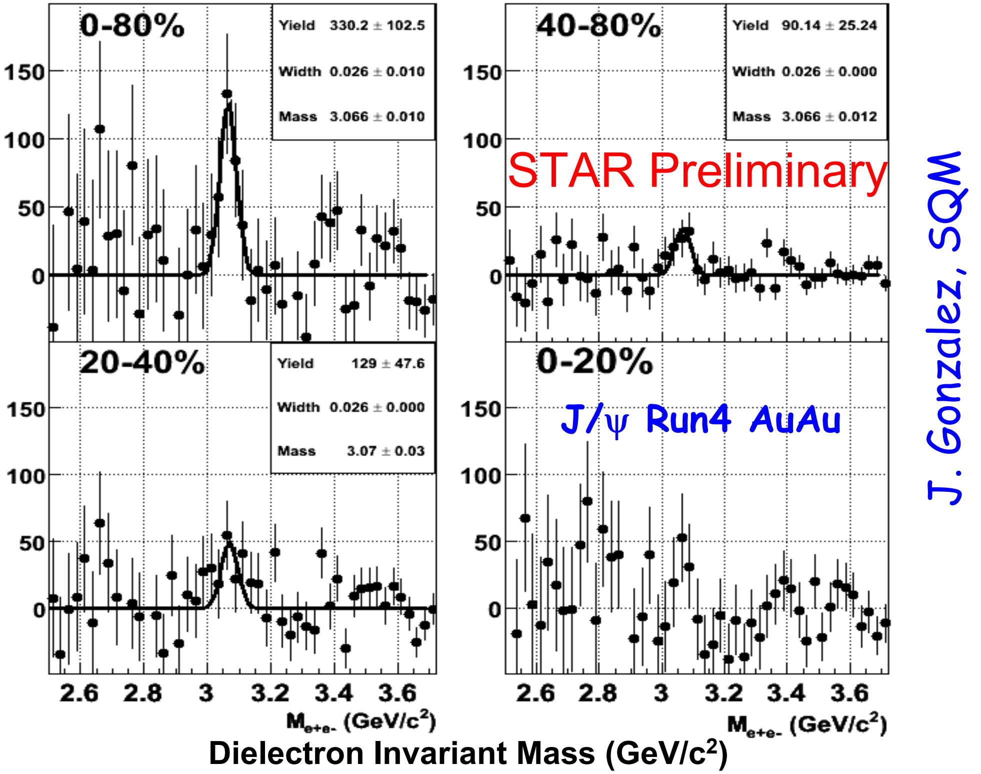
1st Upsilons at RHIC from ~3pb^{-1} collected during the 2005 run.

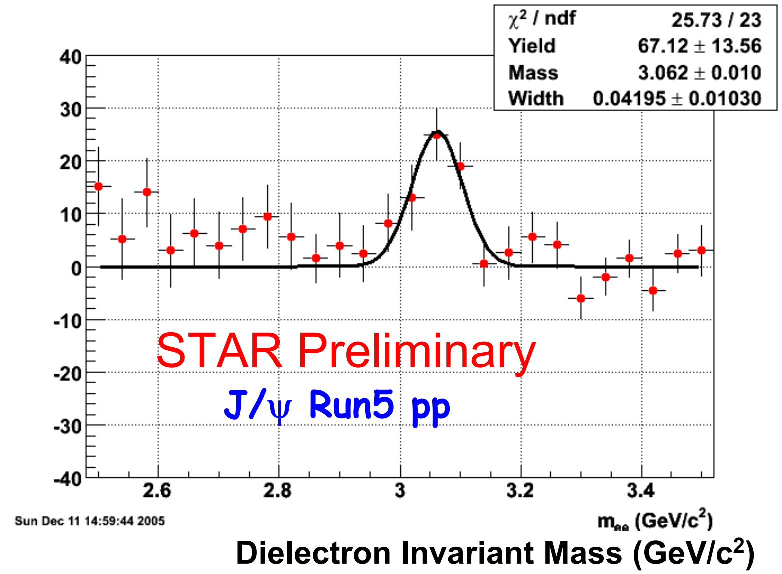
Ultra-peripheral Collisions (UPC's)

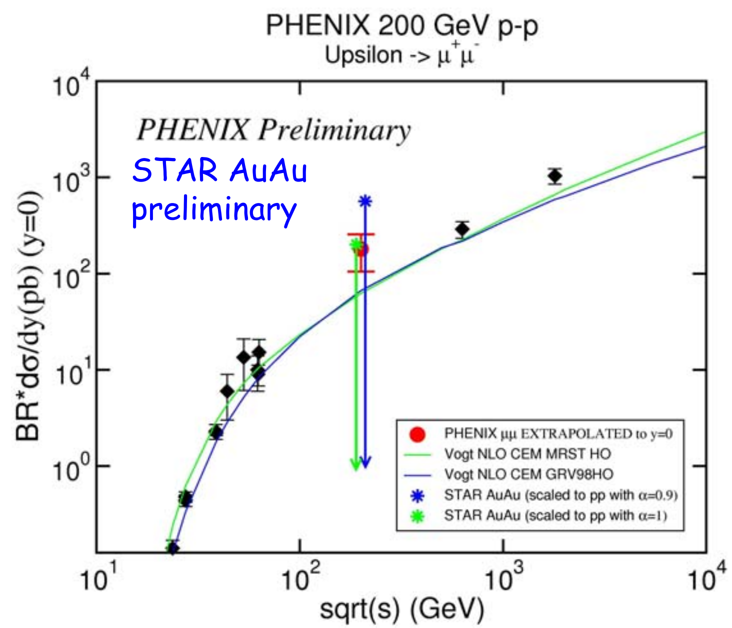


UPC's : well calibrated EM probe of small-x gluon saturation

Onia in STAR







Signal	RHIC Exp. (Au+Au)	RHIC I (>2008)	RHIC II	LHC ALICE+
$J/\psi \rightarrow e^+e^-$	PHENIX	3,300	45,000	9,500
$J/\psi \rightarrow \mu^+\mu^-$		29,000	395,000	740,000
$\Upsilon \rightarrow e^+e^-$	STAR	830	11,200	2,600
$\Upsilon \rightarrow \mu^+\mu^-$	PHENIX	80	1,040	8,400

Summary

Progress on onia production cross sections and polarization but still not well understood

- causes uncertainties in the understanding of nuclear effects (e.g. J/ψ absorption)

Weak shadowing has been observed at RHIC for the J/ψ in dAu collisions

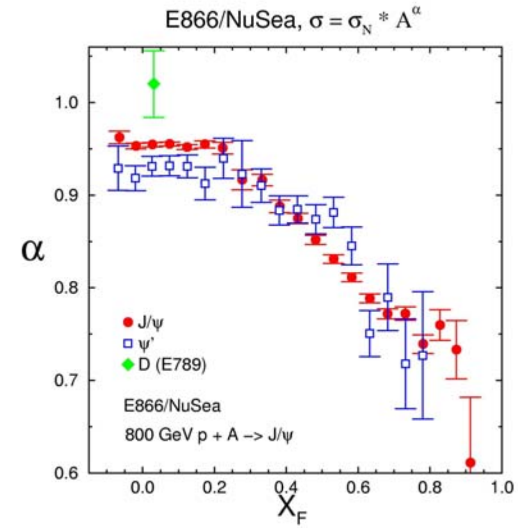
- but scaling with x_F (and not with x_2) is still a puzzle

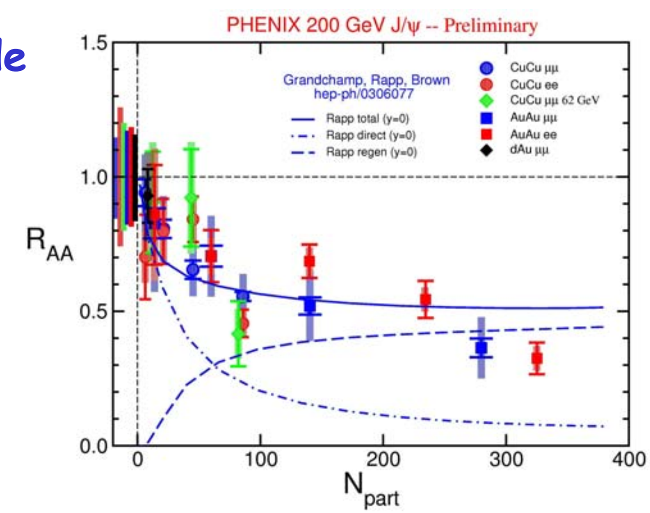
AA collisions at RHIC suggest substantial contributions from regeneration

- suppression observed is very similar to NA50 at lower energies but more suppression would be expected from QGP since gluon densities are 2-3x larger at RHIC

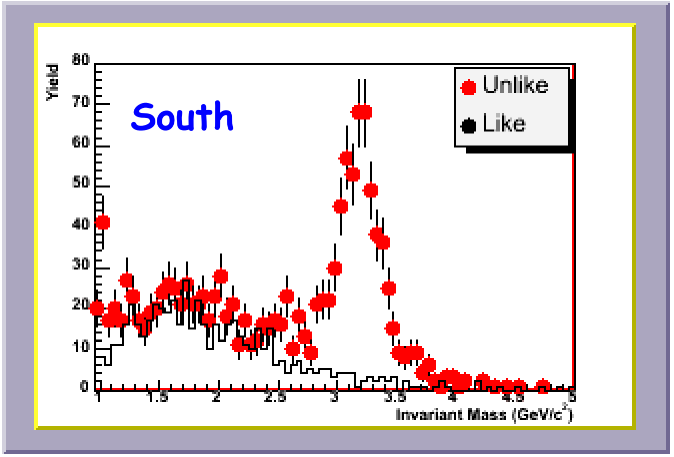
Sequential screening, where χ_c & ψ' are screened but J/ψ is not (consistent with Lattice calculations), provide a simpler picture

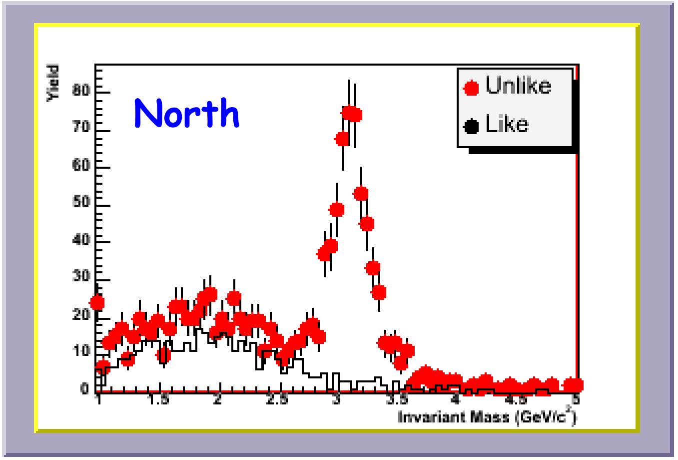
- need more accurate dAu data to establish level of CNM effects in AA
- need accurate open charm cross section & J/ψ flow measurement to constrain regeneration models





PHENIX Run6 (present) J/ψ's in forward/backward Muon arms (from near-online analysis using trigger-filtered events)





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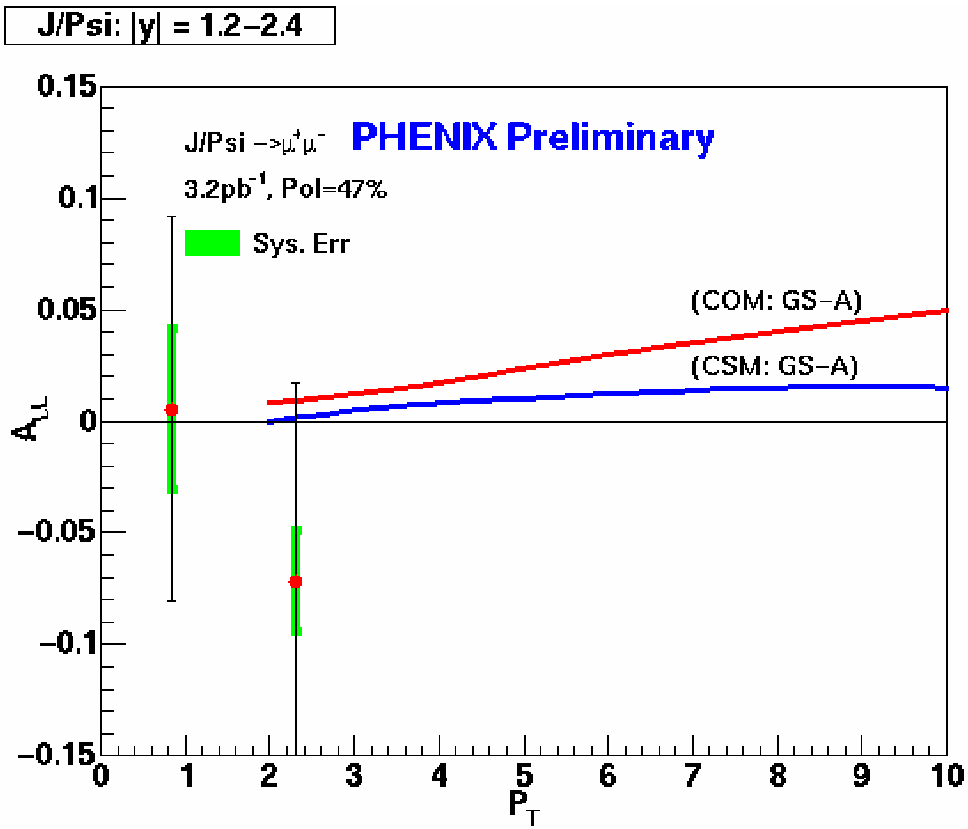
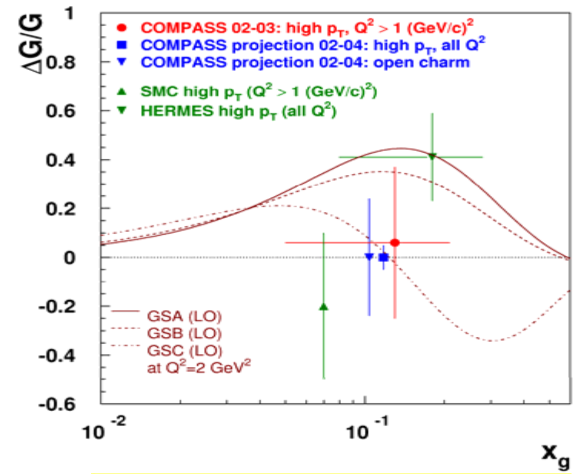
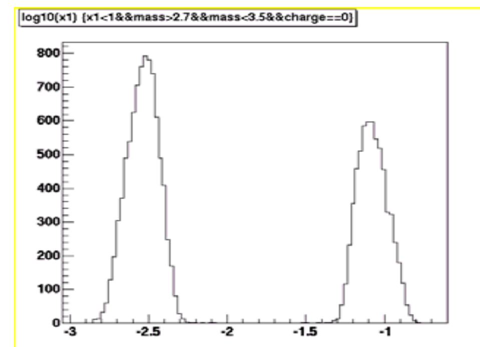
A_{LL} vs p_T







Log(x)

First spin physics result from J/Ψ

- J/ψ: produced via almost pure gluon fusion
- sensitive to gluon polarization

$$A_{LL} \approx \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)} a_{LL}^{gg \to J/\Psi + X}$$

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RHIC-II - Quarkonia

- With detector upgrades (PHENIX and STAR):
  - J/ψ from B decays with displaced vertex measurement (both).
  - Reduce $J/\psi \rightarrow \mu\mu$ background with forward μ trigger in PHENIX.
  - Improve mass resolution for charmonium and resolve Υ family.
  - See γ in forward calorimeter in front of muon arms (PHENIX) and in FMD in STAR

- And with the luminosity upgrade:
  - J/ψ R_{AA} to high p_T. Does J/ψ suppression go away at high p_T?
  - J/ψ v_2 measurements versus p_T. See evidence of charm recombination?
  - Υ R_{AA}. Which Upsilons are suppressed at RHIC?
  - Measure $\chi_c \rightarrow J/\psi + \gamma$ R_{AA}. Ratio to J/ψ?
  - Measure ψ' R_{AA}. Ratio to J/ψ?
  - Measure $B \rightarrow J/\psi$ using displaced vertex - independent B yield measurement, also get background to prompt J/ψ measurement.

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RHIC-II - Heavy Flavor Yields

All numbers are first rough estimates (including trigger and reconstruction efficiencies) for 12 weeks Au+Au run ($\int L_{eff}\,dt \sim 18\ nb^{-1}$)

Signal	RHIC Exp.	Obtained	RHIC I (>2008)	RHIC II	LHC/ALICE+
$J/\psi \rightarrow e^+e^-$ $J/\psi \rightarrow \mu^+\mu^-$	PHENIX	~800 ~7000	3,300 29,000	45,000 395,000	9,500 740,000
$\Upsilon \rightarrow e^+e^-$ $\Upsilon \rightarrow \mu^+\mu^-$	STAR PHENIX	- -	830 80	11,200 1,040	2,600 8,400
$B \rightarrow J/\psi \rightarrow e^+e^-$ $B \rightarrow J/\psi \rightarrow \mu^+\mu^-$	PHENIX	- -	40 420	570 5,700	N/A N/A
$\chi_c \rightarrow e^+e^-\gamma$ $\chi_c \rightarrow \mu^+\mu^-\gamma$	PHENIX	- -	220 8,600	2,900* 117,000*	N/A N/A
$D \rightarrow K\pi$	STAR	~0.4×10⁶ (S/B~1/600)	30,000**	30,000**	8000

* Large backgrounds, quality uncertain as yet
** Running at 100 Hz min bias
+ 1 month (= year), P. Crochet, EPJdirect A1, a (2005) and private comm.

T. Frawley, PANIC'05, RHIC-II Satellite Meeting

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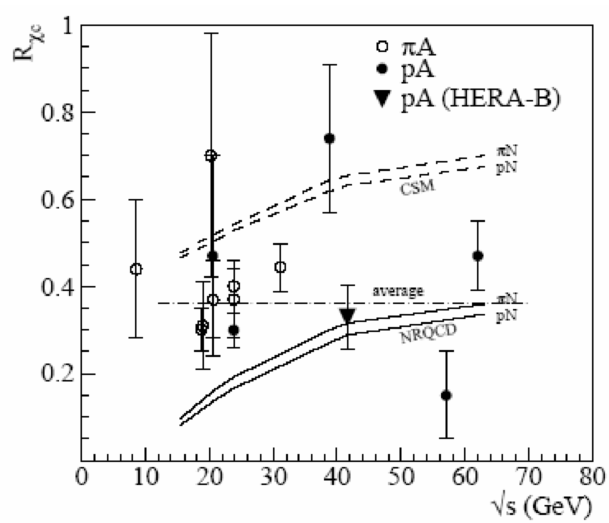
Onia Yields at RHIC II

Signal/System	pp (200 GeV)	pp (500 GeV)	CuCu (200 GeV)	AuAu (200 GeV)	dAu (200 GeV)
$J/\Psi \to ee$	55,054	609,128	73,921	44,614	29,919
$\Psi'(2S) \to ee$	993	10,985	1,333	805	540
$\chi\_c0 \to \gamma + J/\Psi \to ee$	100	2,578	134	81	54
$\chi\_c1 \to \gamma + J/\Psi \to ee$	1,340	40,870	1,800	1,086	728
$\chi\_c2 \to \gamma + J/\Psi \to ee$	2,190	59,296	2,941	1,775	1,190
$\Upsilon(0,1,2) \to ee$	210	3,032	547	397	184
$B \to J/\Psi \to ee$	1,237	41,480	4,567	3,572	1,085
$J/\Psi \to \mu\mu$	468,741	5,483,006	653,715	394,535	258,136
$\Psi'(2S) \to \mu\mu$	8,453	98,880	11,789	7,115	4,655
$\chi\_c0 \to \gamma + J/\Psi \to \mu\mu$	3,822	99,824	5,330	3,217	2,105
$\chi\_c1 \to \gamma + J/\Psi \to \mu\mu$	51,215	1,582,561	71,425	43,107	28,204
$\chi\_c2 \to \gamma + J/\Psi \to \mu\mu$	83,702	2,296,069	116,732	70,451	46,095
$\Upsilon(0,1,2) \to \mu\mu$	528	7,723	1,429	1,035	469
$B \to J/\Psi \to \mu\mu$	2079	76466	5756	3752	1824

- Precision measurements of the J/Ψ
- Exploratory measurements of the other onium states.
- Steep increase at $\sqrt{s}$ = 500 GeV illustrates the significant difficulties for measurements at lower energies.

Feeding of J/ψ's from Decay of Higher Mass Resonances

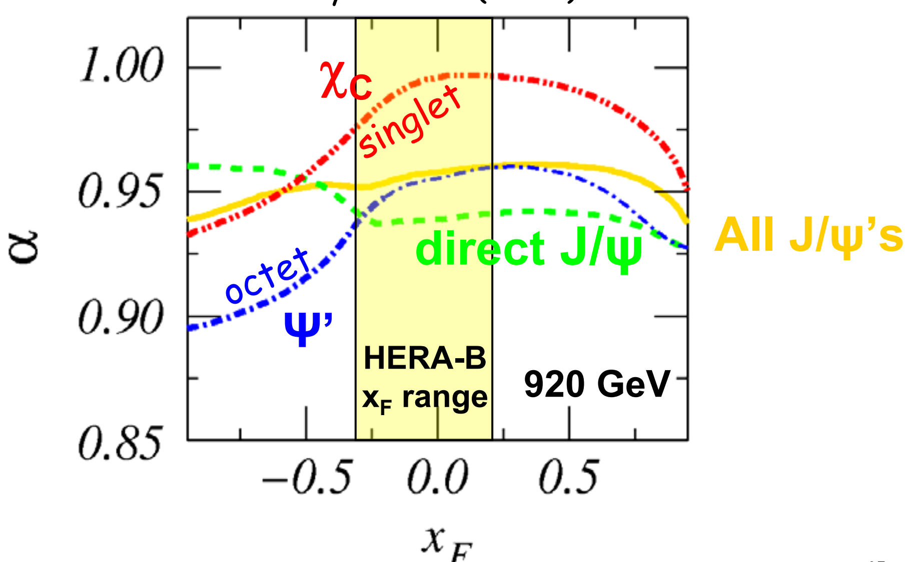


HERA-B Phys.Lett. B561 (2003) 61-72 & E705 @ 300 GeV/c, PRL 70, 383 (1993)

Large fraction of J/ψ's are not produced directly

	Proton	Pion
$\chi_{,1,2} \rightarrow J/\Psi$	~30%	37%
$\Psi' \rightarrow J/\Psi$	5.5%	7.6%

R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539



Effect on Nuclear dependence:

- Nuclear dependence of parent resonance, e.g. χ_C is probably different than that of the J/ψ
- e.g. in proton production ~21-30% of J/ψ's will have different effective absorption because they were actually χ_C's while in the nucleus

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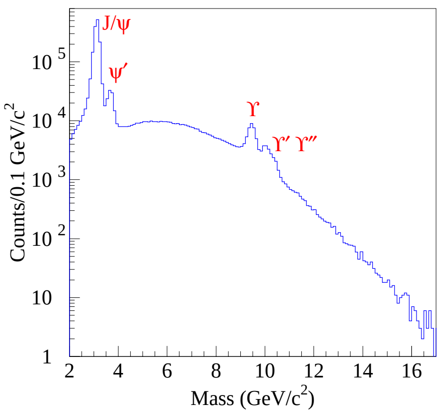
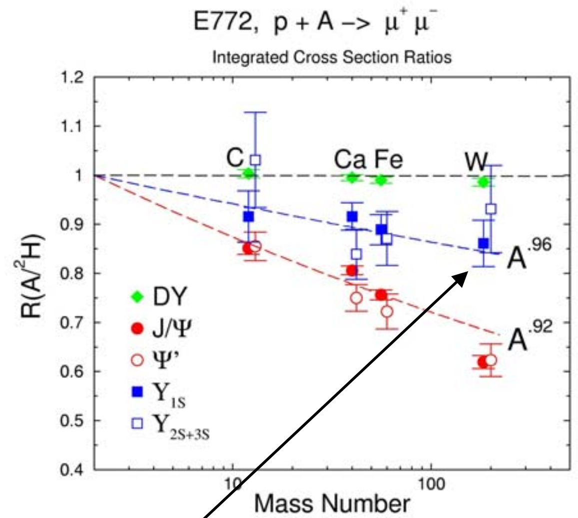
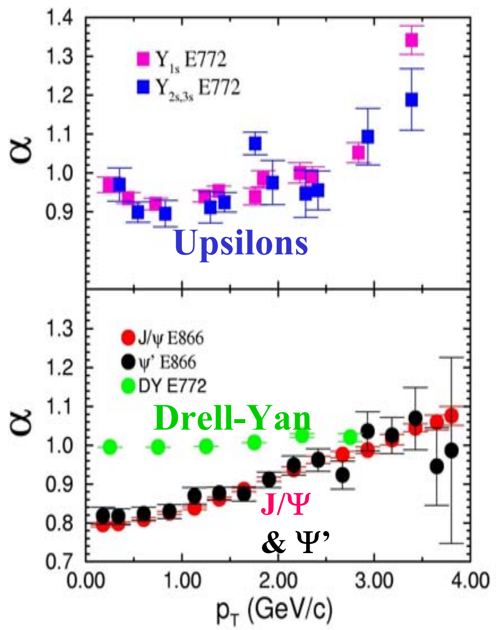
Contrasting Υ's with J/ψ's



$\sqrt{S}$ =39 GeV (E772 & E866)

- less absorption
- not in shadowing region (large x_2)
- similar p_T broadening
- Υ_{2S+3S} have large transverse polarization - unlike Υ_{1S} or J/ψ (as was shown earlier)





But careful: Υ suppression is from data for x_F < 0 or x_2 > 0.2 (in the EMC region)